Experimental Study on Permittivity Estimation Method for UWB Internal Imaging Radar

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***Abstract*—Ultra-wideband (UWB) radar, with high range resolution and ability of penetrating dielectric media, has a great potential for innovative non-destructive testing for aging roads or bridges or non-invasive medical imaging. We have already proposed an accurate permittivity estimation method for a homogeneous dielectric object based on the geometrical optics (GO) approximation, where dielectric boundary points and their normal vectors are directly reproduced by the range point migration (RPM) method. In addition, the finite-difference time domain (FDTD) based waveform reconstruction method was incorporated to compensate for errors incurred by the GO approximation. This paper shows the experimental investigation of this method, where the new approach for suppressing the creeping wave along dielectric boundary is introduced. The results from real observation data validate its effectiveness, in terms of highly accurate permittivity estimation and buried object boundary reconstruction.**

***Index Terms*—UWB radars, Range points migration (RPM), Permittivity estimation, Non-destructive testing**

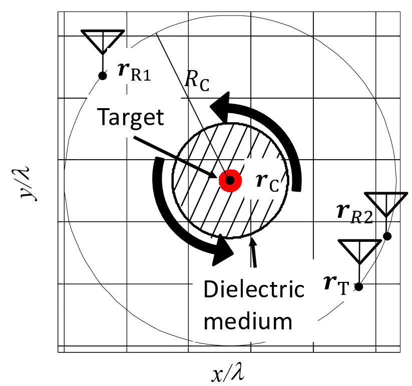

Fig. 1. System model.

I. Introduction

Ultra-wideband (UWB) radar holds high range resolution and a feature for penetrating a dielectric medium, and is promising for various internal imaging applications, such as non-destructive sensing or non-invasive medical imaging. There are various studies for medical imaging for breast cancer detection at an early stage, where a distinguishable echo from malignant tumor is used for localization [1]. However, these studies are based on the classical reconstruction algorithms, such as beam forming or synthetic aperture approach, and such approaches suffers from the limited spatial resolution and reconstruction accuracy and an intensive computation burden. To be more suitable for these applications, we have already proposed an accurate and fast imaging method [2] for targets buried into dielectric medium by extending the range points migration (RPM) method [3]. Although this method offers an accurate internal target image for arbitrary shape in a homogeneous media, it requires a combination use of accurate permittivity estimation method to maintain its imaging accuracy. As a low computational and accurate permittivity estimation method, we have proposed a novel approach by employing outer dielectric boundary accurately reconstructed by RPM and the propagation path estimation based on the geometrical optics (GO) approximation [4]. In addition, this method employs the finite difference time domain (FDTD) method for compensating the estimation error caused by the GO approximation, that is, the transmissive waveform significantly differs from the transmitted one. Since the former study only assesses this method through numerical simulation, this paper experimentally validates this method, where the new approach for suppressing the creeping wave propagating is introduced by using accurately outer dielectric boundary reconstructed by the RPM. The results verify the distinguished feature of the proposed method, that is, an highly accurate internal imaging and permittivity estimation are achieved simultaneously with the experimental data.

II. System Model

Figure 1 shows the system model. A dielectric object is assumed to be a homogeneous, non-dispersive, and lossy medium. One omni-directional transmitting antenna is located at $\boldsymbol{r}_{\mathrm{T}} = (X_{\mathrm{T}}, Y_{\mathrm{T}})$. One receiving antenna is located at $\boldsymbol{r}_{\mathrm{R1}} = (X_{\mathrm{R1}}, Y_{\mathrm{R1}})$, where $\boldsymbol{r}_{\mathrm{C}} = (\boldsymbol{r}_{\mathrm{R1}} + \boldsymbol{r}_{\mathrm{T}})/2$ holds. The other antenna is located at $\boldsymbol{r}_{\mathrm{R2}} = (X_{\mathrm{R2}}, Y_{\mathrm{R2}})$, which is adjacent to the transmitting antenna. The distance from these three antennas to target center $\boldsymbol{r}_{\mathrm{C}} = (X_{\mathrm{C}}, Y_{\mathrm{C}})$ is set to R_{C}. The dielectric object is rotated along the center location $\boldsymbol{r}_{\mathrm{C}}$. A mono-cycle pulse is used as the transmitting signal, the center wavelength of which is defines as λ. $S_{\mathrm{R1}}(\boldsymbol{r}_{\mathrm{R1}}; R)$ and $S_{\mathrm{R2}}(\boldsymbol{r}_{\mathrm{R2}}; R)$ are defined as the outputs of the Wiener filter at antenna positions $\boldsymbol{r}_{\mathrm{R1}}$ and $\boldsymbol{r}_{\mathrm{R2}}$, respectively, where $R = \mathrm{c}t/2$ is expressed by time t and the propagation speed of the radio wave c. The range points extracted from the local maxima in S_{R1} and S_{R2} are defined as $\boldsymbol{q}_{\mathrm{R1}} = (X_{\mathrm{R1}}, Y_{\mathrm{R1}}, R_{\mathrm{R1}})$ and $\boldsymbol{q}_{\mathrm{R2}} = (X_{\mathrm{R2}}, Y_{\mathrm{R2}}, R_{\mathrm{R2}})$, respectively.

III. Proposed Method

The methodology of the proposed method is described as follows. First, this method obtains the outer dielectric boundary points and their normal vectors by applying the RPM method to range points $\boldsymbol{q}_{\rm R2}^{\rm D}$. Here, $\boldsymbol{q}_{\rm R2}^{\rm D}$ denotes the range points having maximal amplitude of $s(\boldsymbol{q}_{\rm R2})$, and $\boldsymbol{q}_{\rm R2}$ except for $\boldsymbol{q}_{\rm R2}^{\rm D}$ are defined as $\boldsymbol{q}_{\rm R2}^{\rm T}$. To obtain target points and normal vectors on the dielectric boundary with a sufficiently small interval, the Envelope interpolation described in [5] is introduced. In most cases, the creeping wave, propagating along outer dielectric boundary is included in the received signal $S_{\rm R1}$, and should be suppressed for permittivity estimation. Here, the propagation distance of the creeping wave from $\boldsymbol{r}_{\rm T}$ to $\boldsymbol{r}_{\rm R1}$ is calculated :

$$R_{\rm creep}(\boldsymbol{r}_{\rm T}, \boldsymbol{r}_{\rm R1}) = \int_{\theta_1}^{\theta_2} R(\theta){\rm d}\theta + \|\boldsymbol{r}_{\rm T} - \boldsymbol{p}^{\rm S}(\theta_1)\| + \|\boldsymbol{r}_{\rm R1} - \boldsymbol{p}^{\rm S}(\theta_2)\|, \quad (1)$$

where $R(\theta)$ denotes the radius of the dielectric outer boundary from $\boldsymbol{r}_{\rm C}$, that is estimated using the Envelope method. $\boldsymbol{p}^{\rm D}(\theta_1), \boldsymbol{p}^{\rm D}(\theta_2)$ are incident and emission points on the dielectric boundary $\mathcal{T}_{\rm Env}$ for the creeping wave, which are determined by the condition that their normal vectors are perpendicular to the radial direction from the transmitting and receiving antennas. In this case, the range points $\boldsymbol{q}_{\rm R1}$ satisfying $|R_{\rm R1} - R_{\rm creep}(\boldsymbol{r}_{\rm T}, \boldsymbol{r}_{\rm R1})| < \delta$ are eliminated, and the remaining range points are defined as $\tilde{\boldsymbol{q}}_{\rm R1}$.

Second, to estimate the dielectric constant for a surrounding outer medium, this method minimizes the difference between an observed and estimated propagation delay. Namely, the relative permittivity calculated for each range point as $\tilde{\boldsymbol{q}}_{\rm R1,i}$ is determined as:

$$\epsilon_{\rm t}^{\rm init}\left(\tilde{\boldsymbol{q}}_{{\rm R1},i}\right) = \arg\min_{\epsilon_{\rm t}} \left| R\left(\epsilon_{\rm t}; \tilde{X}_{{\rm R1},i}, \tilde{Y}_{{\rm R1},i}\right) - \tilde{R}_{{\rm R1},i}\right|^2, \quad (2)$$

where $R(\epsilon_t; \tilde{X}_{{\rm R1},i}, \tilde{Y}_{{\rm R1},i})$ is the estimated propagation delay using the Envelope boundary points $\mathcal{T}_{\rm Env}$ and their normal vectors determined by the GO approximation detailed in [4]. Using all transmissive range points, the initial relative permittivity $\epsilon_t^{\rm init}$ is estimated as:

$$\hat{\epsilon}_{\rm t}^{\rm init} = \frac{\sum_{\tilde{\boldsymbol{q}}_{{\rm R1},i}\in Q} S_{\rm R1}\left(\tilde{\boldsymbol{q}}_{{\rm R1},i}\right) \epsilon_{\rm t}^{\rm init}\left(\tilde{\boldsymbol{q}}_{{\rm R1},i}\right)}{\sum_{\tilde{\boldsymbol{q}}_{{\rm R1},i}\in Q} S_{\rm R1}\left(\tilde{\boldsymbol{q}}_{{\rm R1},i}\right)}, \quad (3)$$

where $Q = \left\{\tilde{\boldsymbol{q}}_{{\rm R1},i} \middle| \left|\epsilon_t\left(\tilde{\boldsymbol{q}}_{R1,i}\right) - \tilde{\epsilon}_t\right| < \Delta\epsilon_t\right\}$, where $\tilde{\epsilon}_t$ is the mode value in $\epsilon_t\left(\tilde{\boldsymbol{q}}_{{\rm R1},i}\right)$ and $\Delta\epsilon_t$ is the threshold to eliminate outliers. Third, to reduce the estimation error caused by the waveform mismatch between transmitted and transmissive waves, the compensation scheme based on FDTD signal regeneration is applied [4]. Lastly, the boundary of the buried target is reconstructed using the extended RPM method in [2].

IV. Performance Evaluation in Experiment

Figure 2 shows the scene of the experimental setup. The cylindrical aluminum (target) is buried into the cylindrical cement (dielectric medium), where both heights of them are 250 mm. Each radius of cement and aluminum object is 139 mm and 25 mm, respectively. The distance from the antenna to the target rotating center as $(X_{\rm C}, Y_{\rm C}) = (400{\rm mm}, 400{\rm mm})$ is 400mm. The received signals are obtained by the VNA (Vector Network Analyzer), where the frequency is swept from 50 MHz to 5550 MHz with 10 MHz interval. $S_{\rm R1}, S_{\rm R2}$ are obtained by applying the inverse discrete Fourier transform to these frequency data. The effective bandwidth and center frequency are both 2.0 GHz, where the range resolution is 75 mm. The actual relative permittivity of the dielectric object (cement) is measured as 9.07 by assessing the propagation delay in observing the cement with cuboid shape. The estimated relative permittivities before and after waveform compensation are 8.52 and 8.80, and the relative error are 6 % and 3% respectively. Fig. 3 shows the estimated dielectric boundary and the buried target boundary points reconstructed by the method described in [2], before and after waveform compensation. The mean error for permittivity estimation before and after waveform compensations are $1.98 \times 10^{-2}\lambda$ and $0.97 \times 10^{-2}\lambda$, respectively. This result verifies that the FDTD based waveform compensation effectively contributes to the accuracy enhancement for inner object imaging.

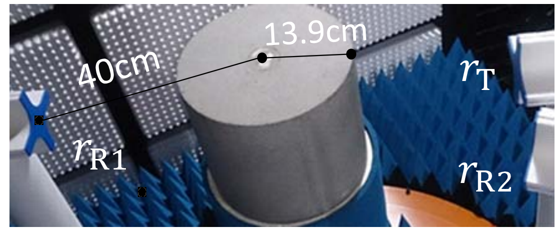

Fig. 2. Experimental setup.

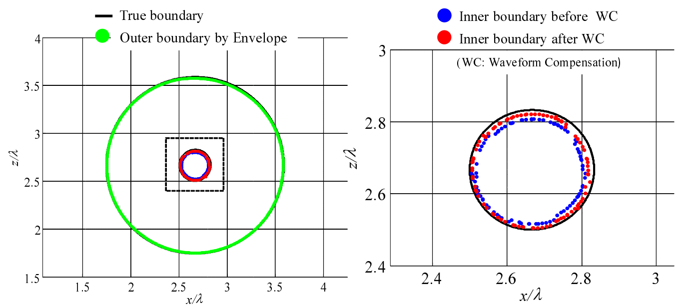

Fig. 3. Reconstructed outer and inner dielectric boundary (right: enlarged image for inner boundary).

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